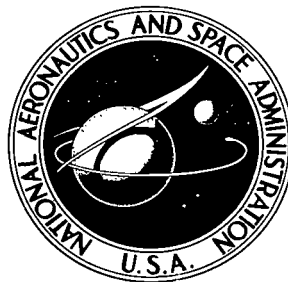


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POLAR CAP ABSORPTIONS AND ASSOCIATED SOLAR-TERRESTRIAL EVENTS THROUGHOUT THE 19TH SOLAR CYCLE

by Yukio Hakura

*Goddard Space Flight Center
Greenbelt, Md.*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1968





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ABSTRACT

Solar cycle variations in the emission of high-energy particles from the sun are examined, by using daily Polar Cap Absorption (PCA) indices, selected solar-terrestrial events, and satellite observations of low-energy solar protons, between 1954 and 1965. A close relationship between PCA's and type IV solar radio outbursts existed throughout the last solar cycle. The solar corpuscular activity showed three peaks in 1957, 1960, and 1963, giving an asymmetric butterfly shape to the latitude-time distribution of type IV sources. The first peak, which coincides with a sole maximum of sunspot numbers, is characterized by a random occurrence of type IV outbursts, PCA's, and geomagnetic SSC's (geomagnetic storms with sudden commencement). Active centers were restricted in two parts of narrow heliographic longitudes during the second, the most prominent peak, giving a slight 27-day recurrence to the corpuscular activity. Finally, a pronounced peak of 27-day recurrence appeared during the third period in spite of a rather decreased corpuscular emissivity. A recurrent series of solar Mev protons lasted 15 solar rotations, while those of geomagnetic Kp index and galactic cosmic ray intensity lasted 25 rotations. The appearance of recurrent Mev protons in the later phase of a solar cycle is controlled not only by the sector structure of the interplanetary space, but also more fundamentally by the energetic proton productivity of the sun.

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POLAR CAP ABSORPTIONS AND ASSOCIATED SOLAR-TERRESTRIAL EVENTS THROUGHOUT THE 19TH SOLAR CYCLE

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Yukio Hakura*

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INTRODUCTION

The sun is a known emitter of energetic particles which cause various electromagnetic disturbances in the earth's upper atmosphere. In particular, during an intense solar flare, it emits not only a magnetized plasma cloud which is responsible for geomagnetic and galactic cosmic-ray storms, but also, on occasions, very high-energy particles known as solar cosmic radiations.

Since the first observation of an unusual increase of cosmic rays in 1942 (Forbush, 1946), at least 14 events with proton energy $E_p > 1$ Bev have been observed by ground-based facilities. Subrelativistic energy particles ($E_p = 1 \sim 1000$ Mev) are not detectable at the ground level, but this information is available from various space vehicles or indirectly from ionosphere observations. These particles emitted from a solar flare precipitate in the polar cap ionosphere, thereby producing an enhanced ionization that causes a severe absorption effect on radio waves. Thus the event is called the Polar Cap Absorption, or PCA (Bailey, 1964; Hultqvist, 1963; Obayashi and Hakura, 1960). Subrelativistic events occur rather frequently; almost 200 outstanding events have been detected by various ionosphere observations since 1938 (c.f. Švestka, 1966; Basler and Owren, 1964).

As possible attributes of a cosmic-ray flare, one may count several particular kinds of landscape or time-variation of the flare observed by various techniques, ranging from radio waves to γ -rays (Ellison, 1963; Kiepenheuer, 1964; Křivský, 1965 and 1966). Among them, dynamic spectral features of solar radio outbursts provide the most promising tool for clarifying the nature of the cosmic-ray flare. Statistical examination of solar radio outbursts and subrelativistic solar protons in the last sunspot maximum shows that the emission of such high-energy particles rises in close association with the occurrence of major type IV outbursts (Hakura and Goh, 1959; Thompson and Maxwell, 1960; Kundu and Haddock, 1960). The relationship seems to be quite reasonable because the type IV outburst is caused by a synchrotron radiation due to highly accelerated electrons

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spiralling in the solar magnetic field; at the same time, the generation of high-energy protons in the excited solar atmosphere can be expected (Boischot and Denisse, 1957).

Satellite observations in the later half of the last solar cycle, however, have revealed numerous increases of low-energy solar protons ($E_p = 100 \text{ keV} \sim 10 \text{ MeV}$) that had apparently little correlation with the type IV radio outbursts. Some of these observations have shown that the MeV protons were confined within a region corotating with the sun which modulated the geomagnetic activity and the galactic cosmic-ray intensity on the orbit of the earth with a 27-day period (Bryant *et al.*, 1965; Fan *et al.*, 1965). The appearance of recurrent geomagnetic disturbances has been known as a prominent feature of the earth storms in the decreasing phase of the sunspot activity (Sinno, 1964).

The solar cycle variation in solar particle radiation is surely one of the most interesting subjects in the field of solar-terrestrial relationships. No relativistic solar cosmic rays were observed during the maximum sunspot activity (c.f. Obayashi, 1964); Švestka (1966), tracing PCA events back to 1938, has shown that the subrelativistic particles also tended to avoid the top of sunspot activity during the last three sunspot cycles. Here, a question arises: "Is the sunspot number a unique measure of solar activity?" The importance of this problem has been emphasized by Gnevyshev (1963), who showed the existence of two peaks of a coronal line intensity observed in the course of the last solar activity. The purpose of the present paper is to list the PCA's and associated solar-terrestrial events that occurred during the 19th solar cycle on a basis of reasonably uniform criteria, and reexamine their casual relationship in various phases of solar activity. Three distinguishable peaks of solar corpuscular activity that appeared in 1957, 1960, and 1963 will be discussed.

POLAR CAP ABSORPTIONS AND ASSOCIATED EVENTS IN YEARS 1954-1965

Daily Indices of f_{\min} Increase

Various ionosphere observations such as VHF forward scatter transmissions, riometers, vertical absorptions, transpolar-cap VLF transmissions, and the f_{\min} of vertical ionosphere sounders (c.f. Sawyer, *et al.*, 1966) are useful PCA detectors. The minimum observable frequency, f_{\min} on vertical sounding ionogram, has some advantages in the worldwide coverage of observing stations and the retrospectivity due to its long observational history.

The value of f_{\min} increases when an abnormal ionization is produced in the polar cap ionosphere by precipitating solar cosmic radiations. When all ionosphere echos are completely absorbed by an intense ionization, the resulting condition is called the "blackout." As an example, a solar-geophysical event of August 16, 1958 is plotted in Figure 1. On that date an intense flare of importance III+, associated with a major type IV radio outburst, occurred at 04:32 UT. Simultaneously with the onset of the flare, a Sudden Ionosphere Disturbance (SID) was noted in an f_{\min} observation at Alert, Canada; this was attributed to an excessive solar X-ray burst emitted from an excited coronal condensation at the time of the flare. A few hours after the SID, f_{\min} began to increase again, indicating the onset of a PCA event. Concurrently, an incidence of solar

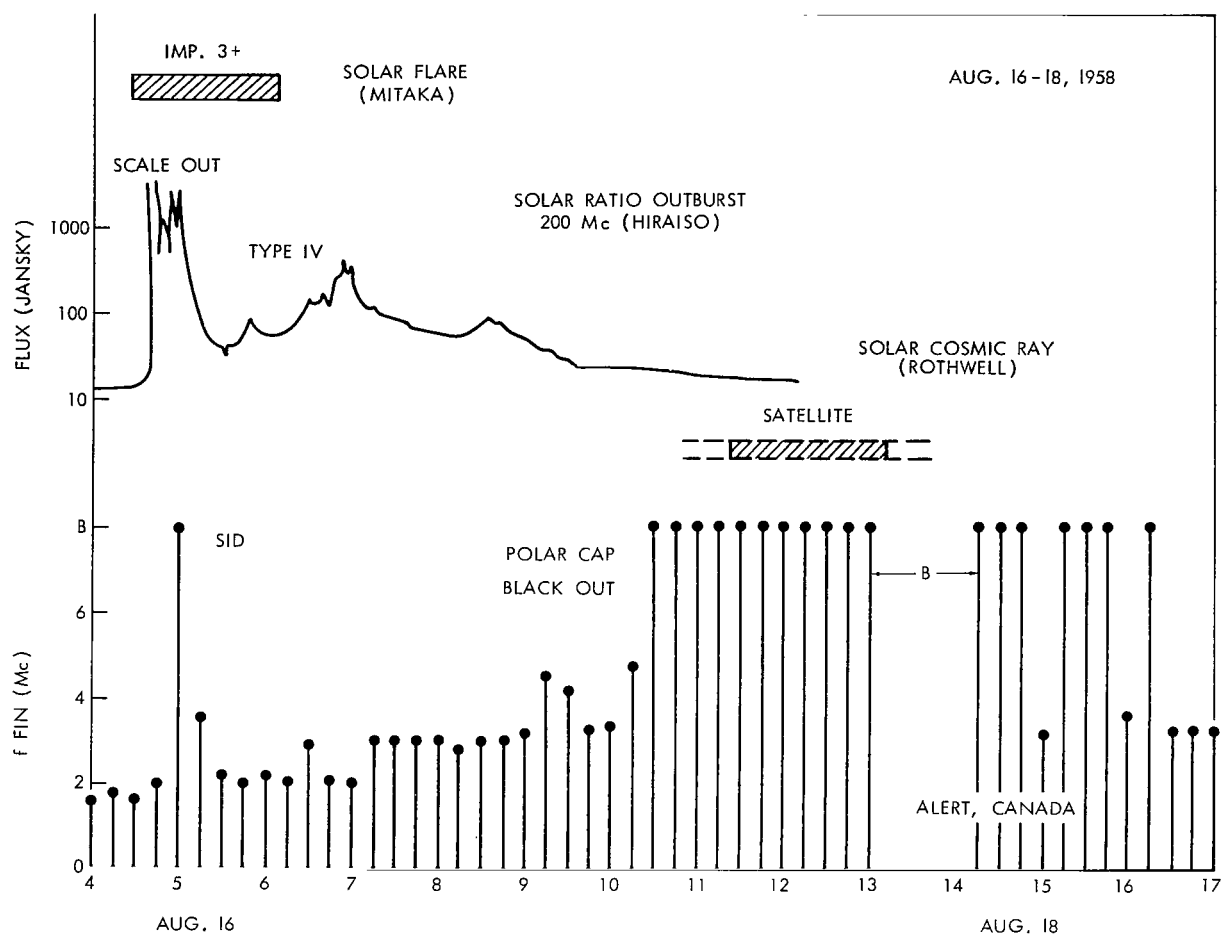


Figure 1—Solar-terrestrial events on August 16-18, 1958.

cosmic-ray protons of energies 10 to 100 Mev was detected by a direct measurement of energetic particles by Explorer 4 in its orbit. The enhancement of f_{min} lasted for about 3 days.

A general morphology of PCA's has been established on a series of synoptic studies of outstanding events observed during the IGY 1957-1958, when an extensive observing network was in operation (Hakura *et al.*, 1958; Obayashi and Hakura, 1960; Hakura and Nagai, 1964; Hakura, 1967). The results have shown that the stations with invariant geomagnetic latitudes greater than 80 degrees are safe from any influence of the auroral-zone absorptions, and thus can be a reliable monitor of PCA events. Canadian data are especially useful because of their long history of observation (since 1949). A number of PCA events have been noted by an examination of f_{min} -time series of Canadian stations (Jelly and Collins, 1962; Jelly, 1963).

In this paper, daily indices of PCA activity were computed for Resolute Bay, Canada (84.3 degrees in corrected geomagnetic latitude, Hakura, 1965), using the following definitions:

N_4 = number of hours per UT day with $f_{min} \geq 4$ Mc/s, and

N_2 = number of hours per UT day with
 $f_{\min} \geq 2 \text{ Mc/s.}$

The indices thus obtained can be a measure of PCA-producing solar cosmic rays, since they indicate some lower limits of total solar cosmic-ray flux in certain energy ranges, impinging upon the polar cap during a day.

The indices were computed for years 1954 to 1965, and the results are displayed in 27-day recurrence tables in Figure 2, where the indices are coded into five grades shown at the top of each table. When the Resolute Bay data were not available, those from Thule, Greenland were supplemented for the missing date. The tables show a general feature of PCA-activity in the whole solar cycle observed with two grades of sensitivity.

Outstanding PCA Events for Years 1954-1965

Using the f_{\min} indices, outstanding PCA events for years 1954-1965 were selected. The middle of Table 1 shows various PCA information such as onset date and time in UT, delay time from an associated flare Δt_a , approximate duration in days, importance, and type.

The importance of a PCA is determined from the f_{\min} indices according to Table 2. Examples of PCA's of importance I, II, and III are shown in Figure 3.

The onset time of a PCA is determined by consulting f_{\min} records of 15-minute intervals and riometers at several polar cap stations. Sometimes the onset time was quoted from published works such as Hakura and Goh (1959), Obayashi and Hakura (1960), Sinno (1961), Obayashi (1962), Yamamoto and Sakurai (1967), and Obayashi (1967).

PCA's are classified into three types according to their delay times from the associated

INDEX FOR YEARS
1954-65

$N_4 = 0 \quad 2 \quad 4 \quad 7 \quad 14$
 TO TO TO
 1 3 6 13 24

INDEX FOR YEARS
1954-65

$N_2 = 0 \quad 2 \quad 4 \quad 7 \quad 14$
 TO TO TO
 1 3 6 13 24

RECURRENCE TABLE

RECURRENCE TABLE

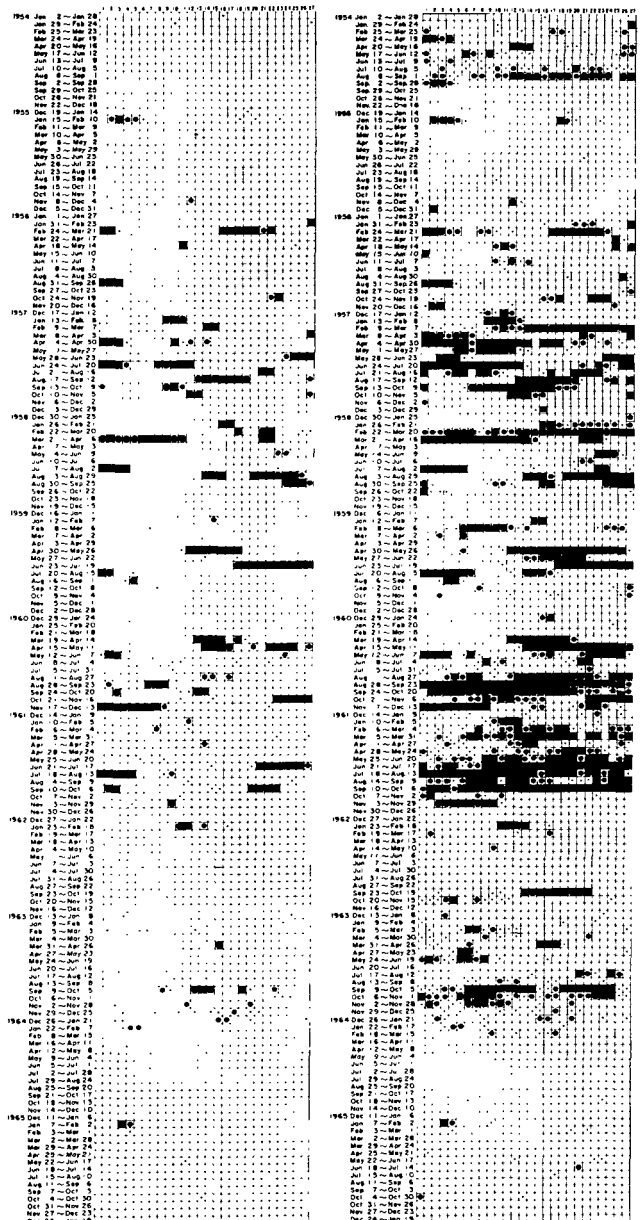


Figure 2—Twenty-seven-day recurrence tables of daily PCA-activity indices, N_4 and N_2 .

Table 1

Outstanding Solar-Terrestrial Events in 1954-1965.

| Year | Month | Solar flare with type IV outburst | | | | | Polar cap absorption | | | | | | Geomagnetic storm | | | | |
|------|-------|-----------------------------------|------|----------|-------|-----------------|----------------------|--------|--------------------|-----------------|------|------|-------------------|------|--------------------|------|------|
| | | Onset date | Time | Position | Imp. | Imp. of type IV | Onset date | Time | Δt_a (hrs) | Duration (days) | Imp. | Type | Onset date | Time | Δt_a (hrs) | Imp. | Type |
| 1954 | V | | | | | | 1 | 0200 | | 3 | I | | | | | | |
| | VIII | | | | | | 19 | | | 13 | I | | | | | | |
| 1955 | I | | | | | | 16 | | | 2 | II | | 17 | 0322 | | II | SSC |
| | II | | | | | | 1 | 0900 | | 1/2 | I | | | | | | |
| | XI | | | | | | 19 | 1200 | | 1/2 | I | | 19 | 1319 | | II | SSC |
| | XII | | | | | | 6 | 0400 | | 1 | I | | 5 | 2216 | | I | SSC |
| 1956 | II | 14 | 0541 | | | B | | | | | | | | | | | |
| | II | 23 | 0334 | N23W74 | III+ | A | 23 | 0415 | 0.7 | 3 | III | G, F | 25 | 0307 | 48 | III+ | SSC |
| | III | | | | | | 10 | 1400 | | 7 | II | | 10 | 1058 | | II | SSC |
| | IV | | | | | | 15 | 0100 | | 1 | I | | 15 | 1628 | | I | SI |
| | IV | 27 | 2100 | N15W34 | II | C | 27 | 2200 | 1 | 1 | II | F | 30 | 0138 | 53 | III | SSC |
| | V | | | | | | 14 | 0500 | | 1 | I | | 13 | 2222 | | III | SSC |
| | VIII | | | | | | 28 | 2300 | | 1 | I | | | | | | |
| | VIII | 31 | 1228 | N18E12 | III | A | 31 | 1500 | 2.5 | 4 | III | F | IX/02 | 0230 | 38 | III+ | SSC |
| | XI | | | | | | 8 | | | 3 | I | | 9 | 2030 | | III | SSC |
| | XI | 13 | 1431 | N16W10 | II | C | 14 | 0000 | 9.5 | 3 | II | S | 15 | 0807 | 42 | III | SSC |
| | XII | | | | | | 25 | | | 3 | I | | 25 | 0754 | | I | SSC |
| 1957 | I | (20 | 1116 | S25W18 | III) | | 20 | 2215 | | 4 | II | | 21 | 1255 | | III | SSC |
| | II | (21 | 1605 | N13W40 | III+) | | 21 | 1800 | | 3 | II | | 23 | 1807 | | III+ | SSC |
| | III | | | | | | 28 | 0900 | | 2 | I | | 29 | 0336 | | I | SSC |
| | IV | 3 | 0825 | S15W60 | III | C | 3 | 1015 | 2 | 7 | III | F | 5 | 1436 | 54 | II | SI |
| | IV | | | | | | 11 | 1300 | | 7 | II | | | | | | |
| | IV | 16 | 1048 | N32E90 | II | C | | | | | | | 17 | 2332 | 37 | I | SI |
| | IV | 17 | 2000 | N12E70 | III+ | C | | | | | | | | | | | |
| | V | | | | | | 19 | 0200 | | 3 | I | | 18 | 1508 | | III+ | SSC |
| | V | | | | | | 5 | 0200 | | 2 | I | | | | | | |
| | V | | | | | | 8 | 0100 | | 4 | I | | | | | | |
| | V | | | | | | 30 | | | 3 | I | | 30 | 0822 | | II | SSC |
| | VI | 19 | 1608 | N20E46 | II | C | 19 | 2215 | 6 | 6 | III | (F) | | | | | |
| | VI | (22 | 0236 | N23E12 | II) | | 22 | 0500 | | 6 | III | | 24 | 0340 | | II | SSC |
| | VII | 3 | 0712 | N14W40 | III+ | B | 3 | 0930 | 2 | 4 | III | F | 5 | 0042 | 42 | III | SSC |
| | VII | 16 | 1740 | S33W28 | III | C | 19 | | | 2 | I | | 19 | 0519 | 60 | I | SSC |
| | VII | 24 | 1816 | S24W22 | III | C | 24 | 2015 | 2 | 1 | I | F | 27 | 1959 | 74 | I | SSC |
| | VII | (28 | 1346 | S24W75 | III) | | 28 | 1500 | | 1 | I | | | | | | |
| | VIII | (9 | 0690 | S09E75 | II) | | 9 | 1500 | | 3 | II | | 12 | 1135 | | III | |
| | VIII | 28 | 0913 | S30E35 | III+ | C | 28 | 2230 | 13 | 3 | III | S | 29 | 1920 | 34 | III | SSC |
| | VIII | 31 | 1257 | N20W02 | III | C | 31 | 1415 | 1.5 | 3 | III | F | IX/2 | 0314 | 38 | III+ | SSC |
| | IX | 2 | 1257 | N11W26 | I+ | B | 2 | 1500 | 2 | 3 | III | F | 4 | 1300 | 48 | III+ | SSC |
| | IX | 11 | 0243 | N11W03 | III | B | 12 | 08 | 29 | 2 | I | S | 13 | 0046 | 46 | III+ | SSC |
| | IX | 12 | 1520 | N10W19 | II | C | 12 | Masked | | | I | | | | | | |
| | IX | 19 | 0400 | N23E01 | III | C | 19 | 08 | 4 | 2 | I | F | 21 | 1005 | 54 | III+ | SSC |
| | IX | 21 | 1340 | N10W08 | III | C | 21 | | | 3 | II | F | 22 | 1345 | 24 | III | SSC |
| | IX | 26 | 1907 | N26E15 | III | C | 26 | 2315 | 4 | 2 | I | F | 29 | 0016 | 53 | I | SSC |
| | X | 20 | 1637 | S25W45 | III+ | B | 21 | 05 | 12 | 2 | II | S | 21 | 2241 | 30 | II | SSC |
| | XI | (5 | 0203 | N38W63 | II) | | 5 | 0700 | | 1.5 | I | | 6 | 1821 | | III+ | SSC |
| | XI | 24 | 0850 | S13E37 | III | C | | | | | | | 26 | 0513 | 44 | II | SSC |
| | XII | 13 | 0215 | N22E90 | | C | | | | | | | | | | | |
| | XII | 14 | 1100 | (N17E75) | II) | C | | | | | | | | | | | |
| | XII | 17 | 0734 | N22E44 | II+ | C | 17 | 1200 | 4.5 | 1 | I | F | 19 | 0937 | 50 | II | SSC |
| 1958 | II | 9 | 2108 | S13W14 | II | A | 10 | 0700 | 10 | 2 | II | S | 11 | 0125 | 28 | III+ | SSC |
| | III | 1 | 0340 | | | C | | | | | | | 3 | 0931 | 54 | I | SSC |
| | III | (11 | 0048 | | III) | | 11 | 0500 | | 2 | II | | 14 | 1212 | | I | SSC |
| | III | 14 | 1508 | S23W80 | III | C | 14 | 1600 | 1 | 2 | II | F | 17 | 0750 | 65 | I | SSC |
| | III | | | | | | 18 | | | 16 | II | | 17 | 0751 | | I | SSC |
| | III | 23 | 0950 | S14E77 | III+ | B | 25 | 08 | 46 | 8 | III | S | 25 | 1540 | 54 | I | SSC |
| | IV | | | | | | 10 | 06 | | 3 | II | | 11 | 2140 | | I | SI |
| | VI | 4 | 2140 | N15W58 | II | C | 5 | 04 | 6 | 2 | I | F | 7 | 0046 | 51 | III | SSC |
| | VI | 6 | 0436 | N15W77 | III | C | 6 | 1345 | 9 | 2 | I | (S) | 8 | 1728 | 61 | I | SSC |
| | VI | 26 | 0300 | N10E49 | II+ | B | | | | | | | 28 | 0713 | 52 | I | SSC |
| | VII | 7 | 0039 | N24W09 | III+ | B | 7 | 0200 | 1.5 | 6 | III | F | 8 | 0748 | 31 | III+ | SSC |
| | VII | 29 | 0303 | S14W43 | III | B | 29 | 0415 | 1 | 2 | I | F | 31 | 1532 | 60 | I | SSC |
| | VIII | 16 | 0432 | S14W53 | III+ | A | 16 | 0715 | 2.5 | 3 | III | F | 17 | 0622 | 26 | III | SSC |
| | VIII | 20 | 0043 | N16E23 | III | C | 21 | 1445 | 38 | 1 | II | S | 22 | 0227 | 50 | II | SSC |
| | VIII | 22 | 1417 | N18W09 | III | C | 22 | 1530 | 1 | 4 | III | F | 24 | 0140 | 35 | III | SSC |
| | VIII | 26 | 0005 | N20W54 | III | A | 26 | 0215 | 2 | 4 | III | F | 27 | 0303 | 27 | III | SSC |
| | IX | 14 | 0830 | S10W71 | III+ | C | 14 | 1045 | 2 | 1 | I | F | 16 | 0930 | 49 | III | SSC |
| | IX | (22 | 1012 | N17W65 | II-) | | 22 | 1430 | | 3 | II | | 25 | 0408 | | III+ | SSC |
| | X | 21 | 2330 | S02W20 | II | B | | | | | | | 22 | 20-- | 21 | III | |
| | X | 24 | 1440 | S04W57 | III | C | | | | | | | 27 | 1523 | 70 | III | SSC |
| | XII | 12 | 1300 | S05W07 | II | C | | | | | | | 13 | 1148 | 23 | III+ | SI |
| | XII | 23 | 0540 | S16E65 | III | C | | | | | | | 25 | 2330 | 66 | II | SI |

Table 1
Outstanding Solar-Terrestrial Events in 1954-1965 (Continued).

| Year | Month | Solar flare with type IV outburst | | | | | Polar cap absorption | | | | | Geomagnetic storm | | | | | |
|------|--------|-----------------------------------|--------|----------|-------|-----------------|----------------------|-------------------|--------------------|-----------------|------|-------------------|------------|------|--------------------|------|------|
| | | Onset date | Time | Position | Imp. | Imp. of type IV | Onset date | Time | Δt_n (hrs) | Duration (days) | Imp. | Type | Onset date | Time | Δt_n (hrs) | Imp. | Type |
| 1959 | I | 7 | 0245 | S12W03 | I | C | | | | | | | 9 | 1459 | 60 | III | SSC |
| | I | (26) | 0013 | N09W42 | II | | 26 | 14 | | 2 | I | | 27 | 1329 | 37 | I | SSC |
| | II | 9 | 0200 | N13E90 | II | C | | | | | | | 11 | 0318 | 49 | II | SSC |
| | II | 12 | 2300 | N12E48 | III+ | C | 13 | ^b 10 | 11 | 4 | I | S | 14 | 1142 | 37 | II | SSC |
| | V | 10 | 2055 | N23E47 | III+ | B | 11 | 0130 | 4.5 | 13 | III | F | 11 | 2328 | 27 | III | SSC |
| | V | 11 | 2010 | N08E39 | II+ | C | Masked | | | | III | F | 12 | 1537 | 20 | II | SI |
| | V | 13 | 0510 | N22E26 | II | C | Masked | | | | III | F | 15 | 0703 | 50 | II | SSC |
| | VI | 09 | 1651 | S20E00 | III+ | B | (10 | 0045 | 8 | 1 | I | S) | 11 | 0909 | 40 | I | SSC |
| | VI | (13 | 1051 | N17E27 | II) | | 13 | 13 | | 4 | I | | | | | | |
| | VII | 9 | 2030 | N18E67 | I | B | | | | | | | | | | | |
| | VII | 10 | 0210 | N22E70 | III+ | A | 10 | 0615 | 4 | >4 | III | F | 11 | 1625 | 38 | II | SSC |
| | VII | 14 | 0342 | N16E07 | III+ | A | Masked | | | >3 | III | F | 15 | 0803 | 28 | III+ | SSC |
| VII | 16 | 2115 | N08W26 | III+ | A | Masked | | | 9 | III | F | 17 | 1638 | 19 | III | SSC | |
| VIII | | | | | | 2 | | | 4 | I | F | | | | | | |
| VIII | 14 | 0130 | N12E28 | II+ | C | | | | | | | 16 | 0404 | 50 | III+ | SSC | |
| VIII | 18 | 1022 | N11W34 | III | C | 18 | 13 | 12.5 | 2 | II | F | 20 | 0412 | 42 | I | SSC | |
| IX | 01 | 1924 | N12E60 | II+ | C | | | | | | | 03 | 1417 | 43 | I | SSC | |
| XI | 30 | 0250 | N08E16 | II | B | | | | | | | | | | | | |
| XII | 21 | 0050 | S03W53 | I | C | (21 | (06) | (5) | 1 | I- | F) | 23 | 1525 | 62 | II | SSC | |
| 1960 | I | 11 | 2040 | N23E05 | III | C | 12 | | | 2 | I | | 13 | 1859 | 46 | II | SSC |
| | I | 15 | 1340 | S20W66 | II | C | | | | | | | 16 | 2114 | 31 | I | SSC |
| | III | 29 | 0650 | N12E31 | III | A | 30 | ^b 1000 | 27 | | I | (s) | 31 | 1036 | 52 | III+ | SSC |
| | III | 30 | 1520 | N11E15 | II+ | B | cont. after SID | | | >2 | III | F | 31 | 2142 | 30 | III+ | SSC |
| | IV | 1 | 0845 | N13W09 | III | C | 1 | 1000 | 1 | >4 | III | F | 2 | 2313 | 39 | III | SSC |
| | IV | 5 | 0215 | N12W62 | III | A | 5 | 10 | 8 | 2 | II | S | 6 | 1628 | 39 | I | SI |
| | IV | 28 | 0130 | S05E34 | III | C | 28 | 0400 | 2.5 | 1 | II | F | 30 | 0132 | 48 | II | SSC |
| | IV | 29 | 0209 | N10W22 | III | A | 29 | 0600 | 4 | 3 | III | G, F | 30 | 1213 | 32 | III+ | SSC |
| | V | 4 | 1015 | N12W90 | III | B | 4 | 1045 | 1/2 | 1 | I | F, F | 6 | 1719 | 55 | II | SSC |
| | V | 6 | 1404 | S10E08 | III+ | C | 6 | ^b 2030 | 6 | 3 | III | F | 8 | 0421 | 42 | II | SSC |
| | V | (9 | 0704 | S10E55 | III+) | | 9 | 11 | | 2 | II | | 11 | 0435 | | II | SSC |
| | V | 12 | 1340 | N30W60 | I | C | 12 | | | 1/2 | I | F | | | | | |
| | V | 13 | 0522 | N30W64 | III+ | A | 13 | 0845 | 3 | 2 | II | F | 16 | 1351 | 80 | II | SSC |
| | V | | | | | | 17 | 21 | | 1 | I | | | | | | |
| | V | 26 | 0851 | N14W15 | II | C | 26 | | | 3 | I | | 28 | 2029 | | I | SI |
| | VI | 1 | 0830 | N28E46 | III+ | C | 1 | 12 | 3.5 | 5 | II | F | 3 | 1731 | | II | SI |
| | VI | 25 | 1200 | N22E05 | III | C | | | | | | | 27 | 0145 | 38 | IV | SSC |
| | VI | 25 | 2040 | N18W04 | III | C | | | | | | | 27 | 1630 | 44 | | |
| | VI | 27 | 0010 | S7E35 | III | C | | | | | | | | | | | |
| | VI | 27 | 2140 | N17W28 | III | C | 28 | | | 2 | I | | 29 | 1939 | 46 | III | SSC |
| | VI | 29 | 0140 | N23W56 | I | C | | | | | | | 30 | 1720 | 40 | II | SSC |
| | VIII | 11 | 1920 | N22E27 | III+ | C | 13 | | | 10 | I | | 14 | 1510 | 68 | I | SSC |
| | VIII | | | | | | 26 | | | 4 | I | | | | | | |
| | IX | | | | | | 1 | | | 2 | I | | 2 | 1158 | | II | SSC |
| | IX | 3 | 0037 | N20E87 | III | B | 3 | 08 | 7 | 8 | III | F | 4 | 1145 | 37 | III | SI |
| | IX | 16 | 1710 | S21E66 | I | C | | | | | | | | | | | |
| | IX | 26 | 0530 | S19W64 | II+ | C | 26 | 08 | 2.5 | 4 | II | F | 29 | 0836 | 75 | II | SSC |
| | X | | | | | | 4 | 1600 | | 4 | II | | 6 | 0237 | | III+ | SSC |
| | X | 11 | 0520 | S18W36 | II | C | | | | | | | 13 | 2147 | 64 | I | SI |
| | X | 29 | 1020 | N22E26 | III | C | 29 | | | 3 | I | | | | | | |
| | XI | 10 | 1010 | N29E28 | III | B | | | | | | | 12 | 1325 | 51 | | |
| | XI | 11 | 0315 | N29E12 | II+ | A | 11 | 04 | 1 | 1/2 | I | F | 12 | 1846 | 40 | III+ | SSC |
| | XI | 12 | 1323 | N27W01 | III+ | B | 12 | 1515 | 2 | >3 | III | G, F | 13 | 1021 | 21 | III+ | SSC |
| | XI | 14 | 0246 | N27W19 | II+ | A | 14 | Masked | | | III | F | 15 | 1304 | 34 | II | SI |
| | XI | 15 | 0207 | N26W32 | III+ | A | 15 | 03 | 1 | >6 | III | G, F | 15 | 2155 | 20 | III | |
| | XI | 20 | 2017 | N25W>90 | I | B | 20 | 2300 | 3 | 5 | III | F | 21 | 2147 | 26 | II | SI |
| | XII | (5 | 1825 | N27E68 | III+) | | 8 | | | 2 | I | | 7 | 1804 | 48 | II | SSC |
| 1961 | II | | | | | | 13 | | | 1 | I | | 13 | 0253 | | II | SSC |
| | II | | | | | | 18 | | | 4 | I | | 16 | 0536 | | II | SSC |
| | II | | | | | | 17 | | | 3 | I | | Kp | >5 | | | |
| | IV | | | | | | 14 | | | 1 | I | | 13 | 1450 | | I | SSC |
| | VI VII | | | | | VI/4 | | | 36 | I | | | | | | | |
| | VII | 11 | 1654 | S06E32 | III | B | 11 | 2000 | 3 | 1 | II | F | 13 | 1113 | 42 | III+ | SSC |
| | VII | 12 | 1000 | S08E22 | III+ | B | 12 | 1115 | 1 | 6 | III | F | 13 | 1113 | 25 | | |
| | VII | 15 | 1520 | N15E17 | III | C | Masked | | | | III | F | 17 | 1825 | 51 | III | SSC |
| | VII | 18 | 0921 | S06W59 | III+ | B | 18 | ^b 1000 | 1 | 5 | III | F | 20 | 0248 | 41 | I | SSC |
| | VII | 20 | 1600 | S05W90 | II | B | 20 | Masked | | | III | F | | | | | |
| | VII | 24 | 0450 | N15E18 | III+ | C | 24 | | | 7 | II | F | 26 | 1950 | 63 | III+ | SSC |
| | VII | 28 | 0230 | N10W37 | II | C | | | | | | | | | | | |
| VIII | | | | | | 1 | | | 23 | I | | 1 | 22.8 | | II | SG | |
| IX | | | | | | 7 | | | 2 | I | | | | | | | |
| IX | 10 | 1950 | N08W80 | I | C | 10 | 2315 | 3.5 | 2 | II | F | 13 | 1554 | 68 | I | SSC | |
| IX | | | | | | 14 | | | 15 | I | | 13 | 1554 | | I | SSC | |

Table 1

Outstanding Solar-Terrestrial Events in 1954-1965 (Continued).

| Year | Month | Solar flare with type IV outburst | | | | | Polar cap absorption | | | | | | Geomagnetic storm | | | | |
|------|-------|-----------------------------------|------|----------|------|-----------------|----------------------|--------|--------------------|-----------------|------|------|-------------------|------|--------------------|------|------|
| | | Onset date | Time | Position | Imp. | Imp. of type IV | Onset date | Time | Δt_a (hrs) | Duration (days) | Imp. | Type | Onset date | Time | Δt_m (hrs) | Imp. | Type |
| 1961 | IX | 28 | 2208 | N13E30 | III | B | 28 | 2315 | 1 | 7 | III | F | 30 | 1847 | 45 | III+ | SSC |
| | XI | 10 | 1434 | N09W90 | I+ | C | 10 | 1515 | 0.7 | 2 | II | F | | | | | |
| 1962 | II | 1 | 0902 | N10W35 | II | C | 1 | 2030 | 11 | 2 | II | S | 4 | 0930 | 72 | II | SI |
| | II | | | | | | 5 | | | 1 | | | | | | | |
| | III | 1 | 1640 | S14W56 | II+ | C | | | | | | | | | | | |
| | IX | 27 | 1505 | N09W10 | I- | C | | | | | | | | | | | |
| | X | | | | | | 6 | | | 9 | I | | 7 | 2026 | | I | SSC |
| 1963 | II | | | | | | 9 | 1845 | | 8 | I | | 9 | 2332 | | III | SSC |
| | IV | 15 | 1034 | S10W07 | II | C | 15 | 1215 | 2 | 4 | II | F | 19 | 0317 | 89 | I | SSC |
| | V | 1 | 0525 | N15E46 | II | C | 1 | 1200 | 7 | 3 | I | (F) | 2 | 2219 | 41 | I | SSC |
| | V | | | | | | 29 | | | 4 | I- | | 27 | 2028 | | I | SSC |
| | VIII | 6 | 0855 | N13W11 | II | C | 6 | 1115 | 2 | 2 | I | F | | | | | |
| | VIII | 9 | 2234 | N07W80 | I | C | 9 | (2315) | (0.7) | 2 | I | F | | | | | |
| | IX | 15 | 0015 | N15E75 | II | A | 15 | 1030 | 10 | >1.5 | I | S | 16 | 2229 | 46 | I | SSC |
| | IX | 16 | 1430 | N12E50 | II+ | B | 16 | 1600 | 1.5 | >2 | I | F | 19 | 0543 | 63 | I | SSC |
| | IX | 18 | 2230 | N12E17 | I | B | 19 | 0543 | 7 | 2 | I | F | 21 | 1413 | | III+ | SSC |
| | IX | 20 | 2350 | N10W09 | II+ | A | 21 | 0300 | 3 | 3 | III | F | 22 | 1601 | 40 | III+ | SSC |
| | IX | 26 | 0638 | N13W78 | III | B | 26 | 1115 | 4.5 | 7 | II | F | 27 | 1942 | 37 | II | SSC |
| | X | | | | | | 12 | | | 1 | I | | 11 | 12 | | | SG |
| | X | 28 | 0230 | N11W25 | III | B | 28 | 0815 | 6 | 2 | I | F | 29 | 1359 | 36 | III | SSC |
| 1964 | III | 16 | 1553 | N06W75 | II+ | B | | | | | | | | | | | |
| 1965 | I | | | | | | 10 | 0900 | | 1 | II | | | | | | |
| | II | 5 | 1753 | N07W25 | II | C | (5 | 1840 | 1 | 2 | I- | (F) | 6 | 1414 | 20 | II | SSC |
| | X | 4 | 0937 | S21W30 | II | B | 4 | 1200 | 2.5 | 1/2 | I- | F | 7 | 0859 | | I | SSC |

Notes: 1. Dates and times are in Universal Time (UT).

2. Durations of PCA's are measured in days.

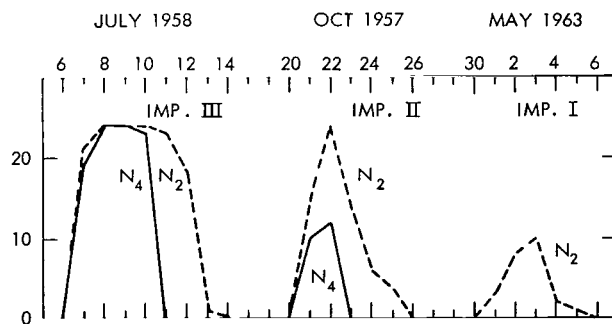
3. Δt_a and Δt_m in hours stand for the delay-times of a PCA and a geomagnetic storm, measured from the onset of an associated flare.4. PCA's are classified into three types, i.e. F-type ($\Delta t_a < 8$), S-type ($\Delta t_a \geq 8$), and others (no associated type IV flare). The sign G stands for a ~ 10 Bev proton event.

5. SSC means a sudden commencement geomagnetic storm, SI a sudden impulse, and SG a gradual geomagnetic storm.

Table 2

Criteria for Determining Importance of a PCA.

| Importance | Criterion |
|------------|--|
| III | When $N_4 \geq 10$ for > 3 successive days |
| II | When $N_4 \geq 10$ for 1 or 2 days |
| I | When $N_2 \geq 10$ for > 1 day |
| I- | When under I, but definitely identified as a PCA from other reliable sources |

Figure 3—Three PCA events of different magnitudes as expressed by daily PCA-activity indices N_4 and N_2 .

type IV-flare: F or fast-onset type ($\Delta t_a < 8$ h), S or slow-onset type ($\Delta t_a \geq 8$ h), and others (no associated type IV outburst). A sign G represents the ground-level solar cosmic ray event with $E_p \sim 10$ Bev.

Associated Events

Table 1 also includes information concerning solar flares, type IV solar radio outbursts, and geomagnetic storms, which presumably have direct connection with the onset of PCA events.

Solar Radio Outbursts of Type IV and Associated Solar Flares

A typical major outburst consists of microwave impulsive bursts followed by outbursts of types III, II, IV_{μ} , IV_{dm} , and IV_m as shown in Figure 4 (Takakura, 1963; Fokker, 1963). Each type

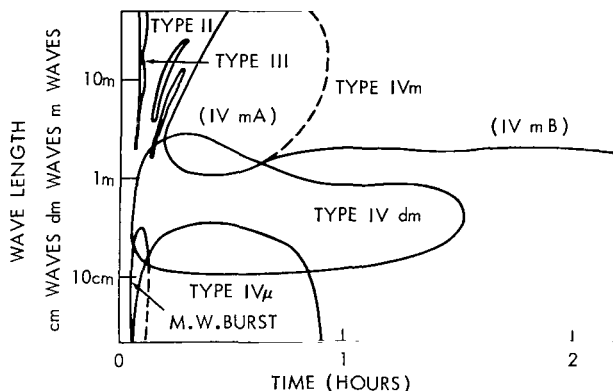


Figure 4—Dynamic spectrum of an intense solar radio outburst.

IV outburst is characterized by its continuous spectra with long durations. Thus, in order to obtain a uniform list of type IV outbursts, dynamic spectral observations with a frequency range of 10 to 10^4 Mc/s at at least three stations well distributed longitudinally are needed. However, with some considerations, type IV outbursts can be selected from single-frequency observations with a few key frequencies, such as 200, 500, 3000, and 9000 Mc/s. Actually the selection of type IV outbursts in the present paper was based on the Netherlands stations at Nera, Holandia, and Paramaribo, which are longitudinally well distributed, and on those at Toykawa, Mitaka, Hiraiso, Berlin, Boulder, and Ottawa.

The result was adjusted in comparison with "A List of Solar Radio Type IV Bursts in 1957 to 1963" made by Kai (1967). An importance A, B, or C was given to each of the outbursts according to their magnitudes. The outbursts of importance A were fully developed and very intense, while those of importances B and C were of medium and minor scale, respectively.

The onset time, location, and importance of a flare associated with the type IV outburst is shown in Table 1, along with the importance of the type IV outburst. The flare information was mainly obtained from Solar-Geophysical Data (CRPL-FB series) issued by Environmental Data Service of ESSA, Boulder, Colorado.

Geomagnetic Storms

The onset date, time in UT, delay time from the flare, importance, and type of associated geomagnetic storm are given also in Table 1. Most of the data are quoted from the table of solar-terrestrial events made by Hakura and Goh (1959), Obayashi (1962), Yoshida (1965). Reports of the Geomagnetic and Geoelectric Observations, 1954 through 1965, issued by Kakioka Magnetic Observatory, Japan, and lists of geomagnetic storms in the *Journal of Geophysical Research* are also used.

It is almost impossible to compile a complete list of solar-terrestrial events that could convince all researchers. Some minor events selected in Table 1 might be different from those selected by others. However, the events listed in Table 1 can be used safely for statistical analysis of the solar-terrestrial relationship since they have been selected on reasonably uniform bases.

RELATIONSHIP BETWEEN PCA'S AND TYPE IV SOLAR RADIO OUTBURSTS

The following paragraphs provide a statistical examination of the relationship between type IV and PCA events observed in the period 1956-1965, in which observations of both types of events are equally available.

PCA-Producing Probability of Type IV Outbursts

The second and third columns of Table 3 show the number and percentage of type IV outbursts associated with PCA's. Among 116 outbursts, 87 events (75 percent) were followed by PCA's. Moreover, among 29 outbursts without PCA, 22 events (76 percent) were minor events of importance C, and major outbursts of importance A were always followed by PCA's, as shown in Table 4.

Table 3

| PCA-Producing Probability of Type IV Outburst for Years 1956-1965. | | |
|--|--------------------------|------------|
| Condition | No. of type IV outbursts | Percentage |
| With PCA | 87 | 75 |
| Without PCA | 29 | 25 |

Table 4

| Number of Type IV Outbursts Without PCA. | | |
|--|--------|------------|
| Magnitude | Number | Percentage |
| A | 0 | 0 |
| B | 7 | 24 |
| C | 22 | 76 |

PCA's Associated with Type IV Outbursts

Table 5 shows the number and percentage of PCA's associated with type IV outbursts. Among 131 PCA's, 87 events (66 percent) were related to type IV outburst. Among 44 PCA's that cannot be related to any type IV outburst, 30 events (68 percent) were minor PCA's of importance I (Table 6). As a result, it is evident that a close relationship between type IV outbursts and PCA's, pointed out by Hakura and Goh (1959) using the IGY data, holds especially for events of major importance.

The correlation between both events increases when propagation conditions for PCA-producing particles in the interplanetary space are considered. Actually, our data confirm the east-west longitudinal asymmetry of PCA-producing probability as well as the deficiency of PCA-occurrence in the northern winter months, for which a number of discussions exist (see Obayashi, 1962; Švestková and Švestka, 1966).

Table 5

PCA's Associated With Type IV Outbursts.

| Condition | No. of PCA's | Percentage |
|-----------------|--------------|------------|
| With type IV | 87 | 66 |
| Without type IV | 44 | 34 |

Table 6

PCA's Without Type IV Outbursts.

| Importance | Number | Percentage |
|------------|--------|------------|
| I | 30 | 68 |
| II | 13 | 30 |
| III | 1 | 2 |

Let us denote for a certain time or space interval:

$N(O)$ = the number of type IV outbursts which did not produce any PCA event, and

$N(P)$ = the number of type IV outbursts which produced PCA events.

Then, the PCA-producing probability P is defined as $P = N(P)/(N(P) + N(O))$.

Figure 5 shows PCA-producing probabilities of type IV outbursts in six heliographic longitude intervals. The well-known east-west asymmetry is evident suggesting that the twisted interplanetary magnetic field gives a more favorable propagation condition to the solar cosmic rays originating in the western part of the solar disk than to those in the eastern part. Figure 6

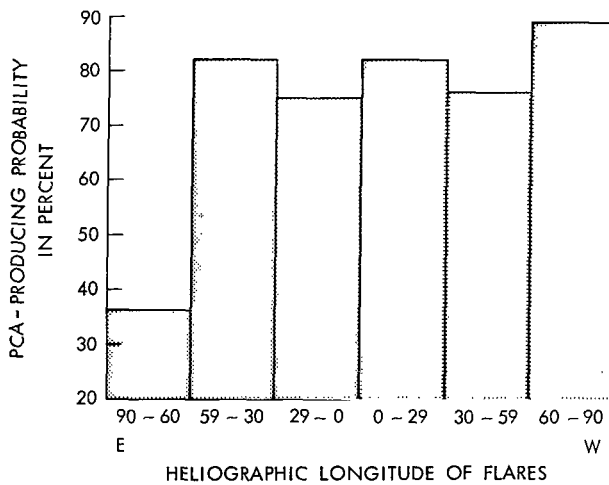


Figure 5—PCA-producing probabilities of type IV sources in six heliographic longitude intervals, inferred from the locations of associated flares.

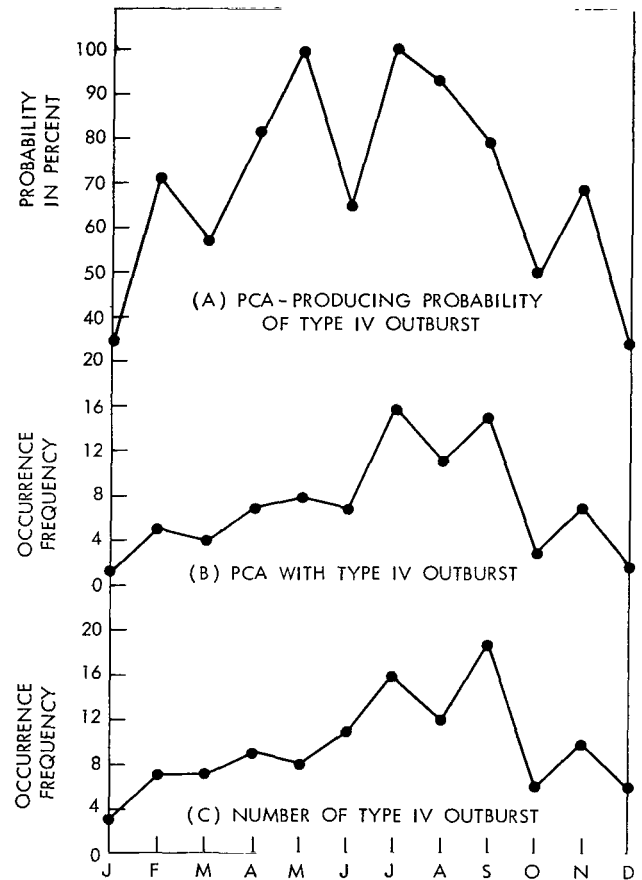


Figure 6—(a) PCA-producing probability of type IV outburst, (b) number of PCA's with type IV and (c) number of type IV outbursts, for each month, January through December.

shows seasonal variations in (a) PCA-producing probability of type IV outbursts P, (b) number of PCA's with type IV outbursts $N(P)$, and (c) number of type IV outbursts $N(P) + N(O)$ for years 1956-1965. The PCA-producing probability shows a deficiency in the northern winter months, though the probability was obtained by excluding a by-chance-seasonal variation of type IV outbursts shown in (c). The deficiency exists even after correcting for a seasonal effect, using data from the southern hemisphere.

SOLAR CYCLE VARIATIONS IN THE CORPUSCLE ACTIVITY OF THE SUN

Figure 7 shows variations in (a) annual mean of Zürich sunspot numbers, (b) occurrence frequency of type IV outburst per year, and (c) number of PCA's (total, identified ground-level events of solar cosmic radiations, fast and slow type events) for years 1954-1965. Variations of type IV outbursts and PCA's are roughly parallel throughout the whole solar cycle, showing again that the principal cause of solar cosmic radiations responsible for PCA's is a flare with type IV solar radio outbursts. The affinity is especially close between the occurrence frequencies of type IV outbursts and fast-onset type PCA events, while most well-defined PCA's of the slow-onset type occurred near the maximum of the sunspot number curve.

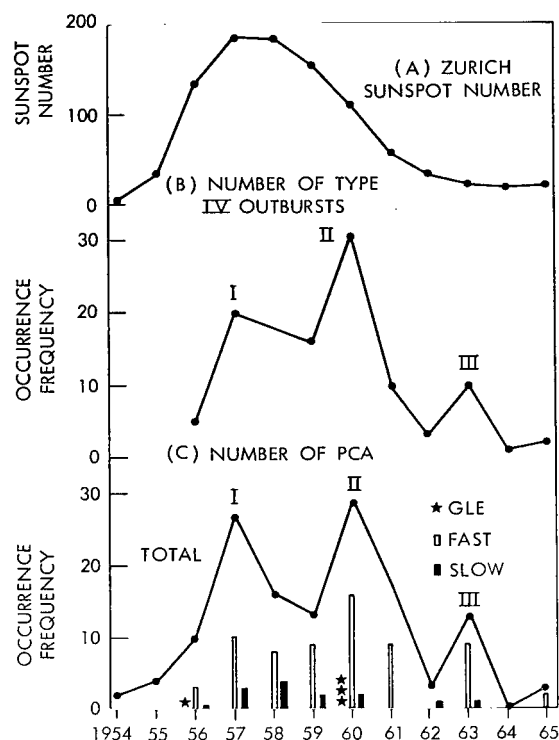


Figure 7—(a) Annual mean of Zürich sunspot numbers, (b) number of type IV outbursts, and (c) number of PCA's (total, identified GLE, fast-, and slow-onset types) for years 1954-1965.

In Figure 7 three peaks of PCA occurrence frequency occur in 1957, 1960, and 1963, in contrast with the unimaximum curve of Zürich sunspot numbers. The existence of two major peaks in 1957 and 1960 has been known by several investigators including Sawyer *et al.* (1966), Švestka (1966), and Gnevyshev and Krivský (1966). Švestka, retracing PCA events for the last three sunspot cycles, related these two peaks to a general tendency of PCA occurrence frequency peaks to avoid the top of the solar activity curve. The tendency is especially evident for the GLE (ground level events of solar cosmic radiations) as seen in Figure 7. Gnevyshev and Krivský connected the sunspot cycle variations of PCA's with those of coronal intensity by showing that proton flares develop in regions of enhanced coronal brightness, which showed two maxima in 1957 and 1960 (Gnevyshev and Ol', 1966). In this paper, the list of PCA's and related events is based on somewhat uniform criteria throughout the last sunspot cycle. It is worthwhile to make a further detailed study of solar cycle variations.

Figure 8 shows (a) heliographic latitudes of PCA-producing flares and (b) annual occurrence frequencies of northern and southern flares for the years 1954-1965. In his survey of solar

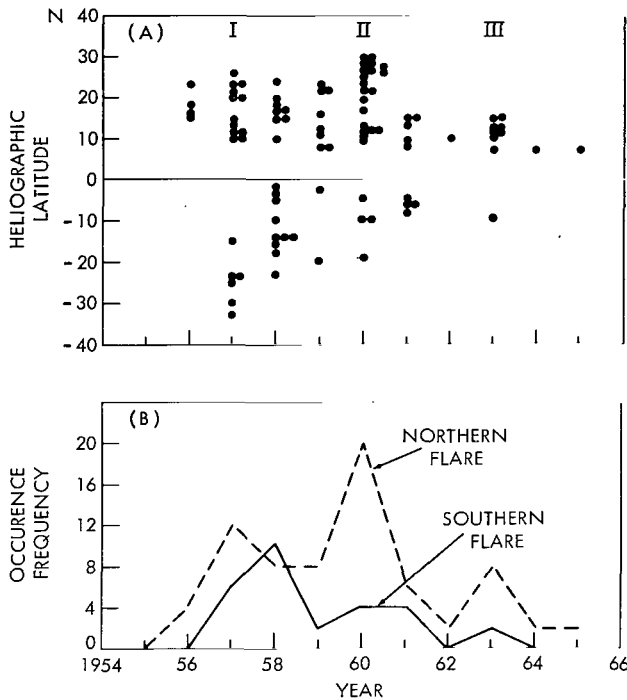


Figure 8—(a) Heliographic latitudes of PCA-producing flares and (b) annual occurrence frequencies of northern and southern flares, 1954-1965.

southern distribution shows a single butterfly pattern. This result, together with the one shown in Figure 8(b) suggests that the last solar cycle consisted of two outstanding peaks of activity and one rather small one, in 1957-1958, 1960, and 1963, respectively.

Localization of PCA-producing centers is often seen on the solar disk. For example, three outstanding PCA events were observed in July 1959, in association with three flares that occurred successively in the same MacMath plage region, on July 10, 14, and 16. It is interesting to examine the absolute longitudinal distribution of PCA sources during the whole course of solar activity.

Let us denote:

d = date of flare observation expressed by $(\text{date} + \text{hour}/24)$, and

l = apparent heliographic longitude of the flare.

Then, the data of the CMP (central meridian passage) of the flare are approximately given by

$$d' = d - \frac{27}{360} l$$

disturbances associated with PCA events, de Jager (1966) called attention to the north-south asymmetry of flare activity—the occurrence of more PCA sources in the northern solar hemisphere than in the southern hemisphere during the last three cycles. A detailed structure of the north-south asymmetry is seen in Figure 8(b); there are three peaks in the occurrence frequency of PCA-producing flares in the northern hemisphere, and one in the southern hemisphere in 1958.

The distribution of PCA flares in the latitude shown in Figure 8(a) is interesting in comparison with Maunder's butterfly diagram. Examining the latitudinal distribution of sunspots from 1874 to 1913, Maunder (1922) showed that the first spots of a cycle occur at approximately 30°N and 30°S. At sunspot maximum, the zones reach ± 15 degrees latitude, and the last spots of a cycle appear at approximately ± 8 degrees. The pattern obtained here seems to show details of the Maunder diagram; the northern diagram consists of three (or two) separate parts, and the

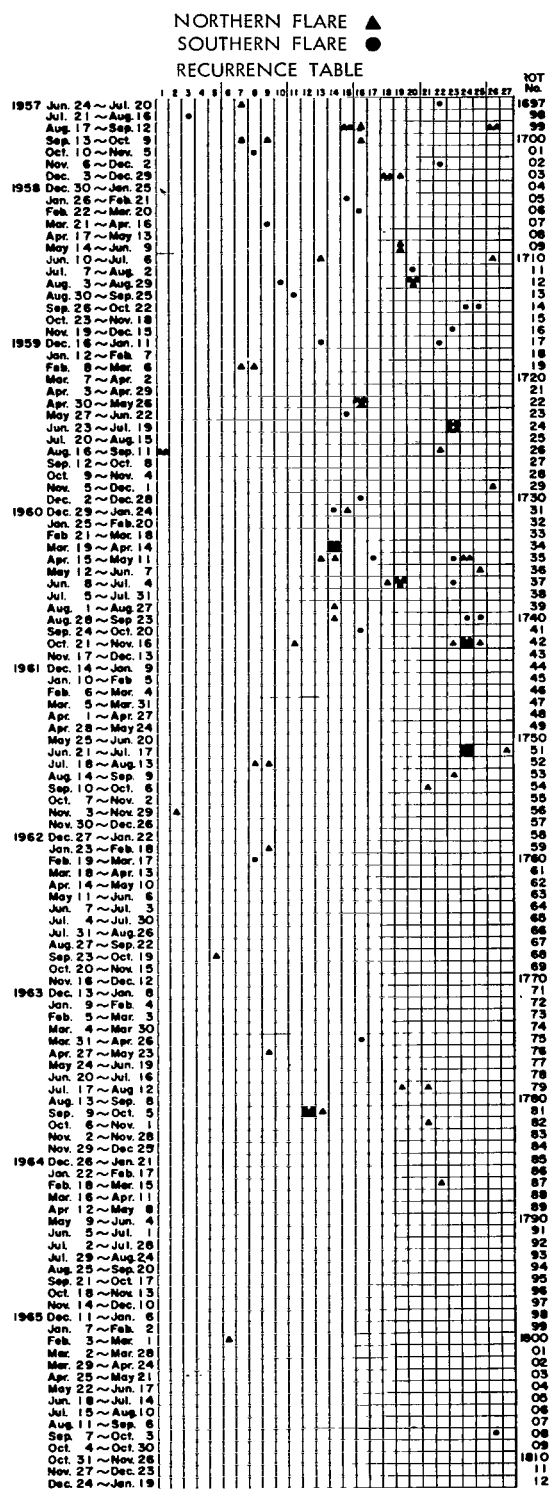


Figure 9—Distribution of CMP dates of PCA-producing flares in the northern and southern hemispheres, on 27-day recurrence chart.

Figure 9 shows the distribution of CMP dates of PCA-producing flares in the northern and southern hemispheres on a 27-day recurrent chart. There is a tendency for the PCA flares to occur in the same active region even for a few solar rotation periods.

Figure 10(d) summarizes the longitudinal distribution of the CMP dates for solar rotation numbers 1697–1795, i.e. July 24, 1957 through October 17, 1964. There are two inactive regions on days 2–6 and 17 and four active regions on days 8–9, 12–17, 19–20, and 23–24, during the whole period of the last solar activity. Figure 10(a) through 10(c) gives the distributions in three different phases of solar activity: (a) solar

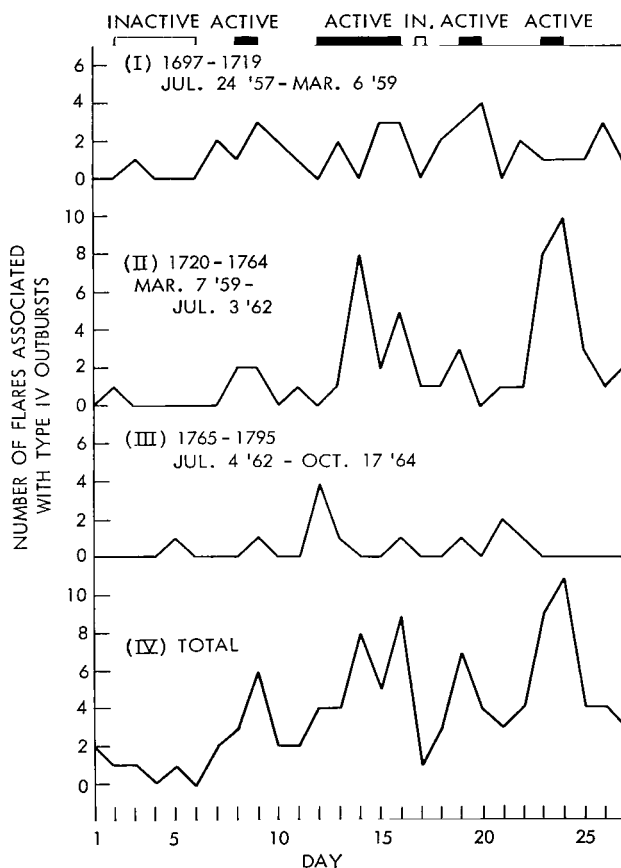


Figure 10—Longitudinal distributions of the CMP dates of type IV sources, for solar rotation numbers (a) 1697–1719, (b) 1720–1764, (c) 1765–1795, and (d) total.

rotation numbers 1697-1719, July 24, 1957 through March 6, 1959; (b) solar rotation numbers 1720-1764, March 7, 1959 through July 3, 1962; and (c) solar rotation numbers 1765-1795, July 4, 1962 through October 17, 1964.

In the period (a) which included the first peak of PCA activity, there were at least four active centers, and their longitudinal distribution looks rather random. On the other hand, the active regions were restricted in two parts of narrow heliographic longitudes in the periods (b) and (c) (c.f. Sakurai, 1966), though the positions of active regions were somewhat different in the two periods. The localization of activity was especially outstanding in period (a) which included the second peak of PCA activity.

It is believed that the interplanetary magnetic field is generated as a result of the transport of the solar magnetic field with the outflowing solar plasma. The localization of solar active centers might mean the simplification of interplanetary field in the declining period of sunspot activity (II) and (III), from the complexity observed in the maximum period (I). Actually, in 1963, the satellite IMP-1 revealed a simple sector pattern of the interplanetary space that lasted for more than several solar rotations (Ness *et al.*, 1964).

RECURRENT GEOMAGNETIC STORMS AND SOLAR COSMIC RADIATION

Figure 11 shows sunspot cycle variations in the annual mean of ΣK_p , the 27-day autocorrelation coefficient of ΣK_p , and numbers of two different kinds of geomagnetic storm, SC- and G-types, observed at Kakioka, Japan. The SSC's occur rather sporadically and may be connected with the onset of major flares in the central regions of the solar disk. The SG's start gradually, last for a week or more, and sometimes recur with an approximate 27-day period.

In Figure 11 there are two sets of affinity between ΣK_p and SSC, and autocorrelation coefficient and SG. It is easily seen that two outstanding peaks of ΣK_p in 1957 (I) and 1960 (II) are mainly caused by the occurrence of SSC's. Because of the sporadic nature of the SC storm, the 27-day autocorrelation coefficient of ΣK_p showed very low value during the first peak of geomagnetic activity, 1957-1958. A slight enhancement of the coefficient seen in 1960 (II) is due to the locality of flare sources shown in Figure 10. Since the geomagnetic storm-producing probability shows a maximum at the CMP of source flares, the locality

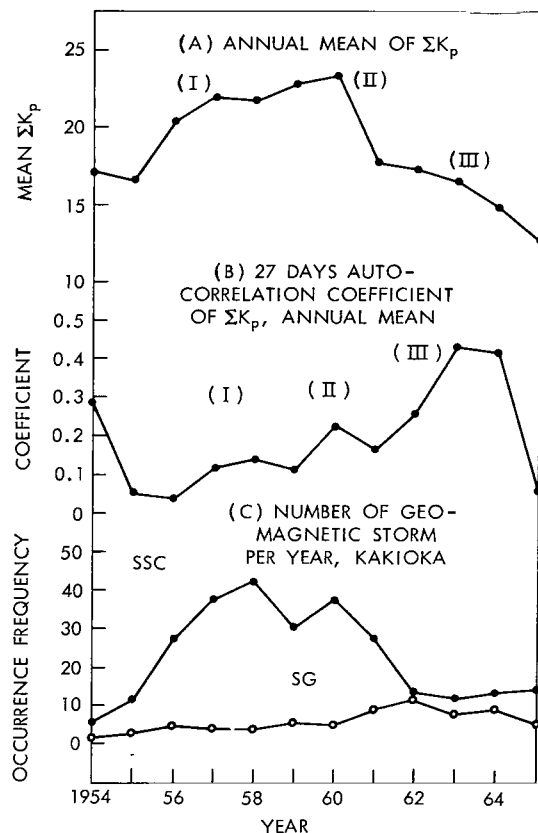


Figure 11—Solar cycle variations in (a) annual mean of ΣK_p , (b) 27-day autocorrelation coefficient of ΣK_p , and (c) numbers of SC and G-type geomagnetic storms observed at Kakioka, Japan.

of type IV sources causes some recurrency in spite of the sporadic nature of the flare occurrence itself.

Another interesting problem seen in Figure 11 is an inverse relationship of ΣKp value to its recurrency, in 1961-1964. It is known that the ΣKp value is linearly related to a daily average of solar wind velocity (Snyder *et al.*, 1963) and the interplanetary magnetic field magnitude (Wilcox *et al.*, 1967). Thus, the inverse relationship shows that a traffic regulation of 27-day periodicity was established during the end of solar cycle (III) when the solar wind velocity and the interplanetary field became lowered.

Generally speaking, the 27-day autocorrelation coefficient of ΣKp showed a gradual increase toward the sunspot minimum from 1956 to 1964. A similar tendency is seen in the variation of G-type geomagnetic storms. If we assume the occurrence frequency of the SG as representative of the recurrency, we can see a secular variation of the recurrency for four solar cycles from 1924 to 1965 in Figure 12, where occurrence frequencies of SC storms, non-SC storms (SG's), and sunspot numbers are given. The non-SC recurrent storms show a sawtooth distribution with an 11-year period. This, along with a possible periodicity of three solar cycles, might afford a tool for long-term prediction of the recurrence.

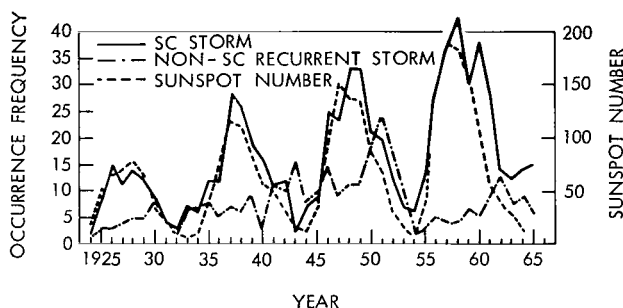


Figure 12—Occurrence frequencies of two kinds of geomagnetic storms per year, observed at Kakioka, and Zürich sunspot numbers for the years 1924-1965.

Evidence for the 27-day recurrent PCA was first shown by Gregory and Newdick (1964) and later criticized by Basler and Owren (1964) using 105 well defined events from Jan. 1957 to Feb. 1962. However, it is obvious from our results that the recurrence of PCA's should be examined for the data obtained during the low solar active period, when the geomagnetic recurrence becomes predominant. Figure 13 shows day-to-day variations in N_2 and N_4 indices for six solar rotations (1773-78). This period is especially interesting since Bryant *et al.* (1965) have presented a clear recurrence of Mev proton events using the Explorer XIV satellite data. Associated phenomena such as solar flares, type IV solar radio outbursts, and geomagnetic storms are indicated by the symbols shown in the top of the figure. Except for a type IV-associated event on April 15, four other detectable PCA events in the present period occurred with approximately 27-day recurrence, starting on days 5-6 in the recurrence table (Figure 2). If we assume these PCA's to be identical with Mev solar proton events, then the recurrent events persisted for the whole period considered here.

Figure 14 shows the relationship between the Mev proton flux given by Bryant *et al.* (1965), and N_2 index of PCA's obtained from Figure 13. Among nine events, eight proton events are well above the threshold value, while only six events can be identified as PCA's (four definite PCA's of Imp. I, a PCA of Imp. I-, and a doubtful PCA of Imp. I--). The result clearly shows the superiority of the satellite data to the ionospheric absorption measurement for the detection of solar Mev proton

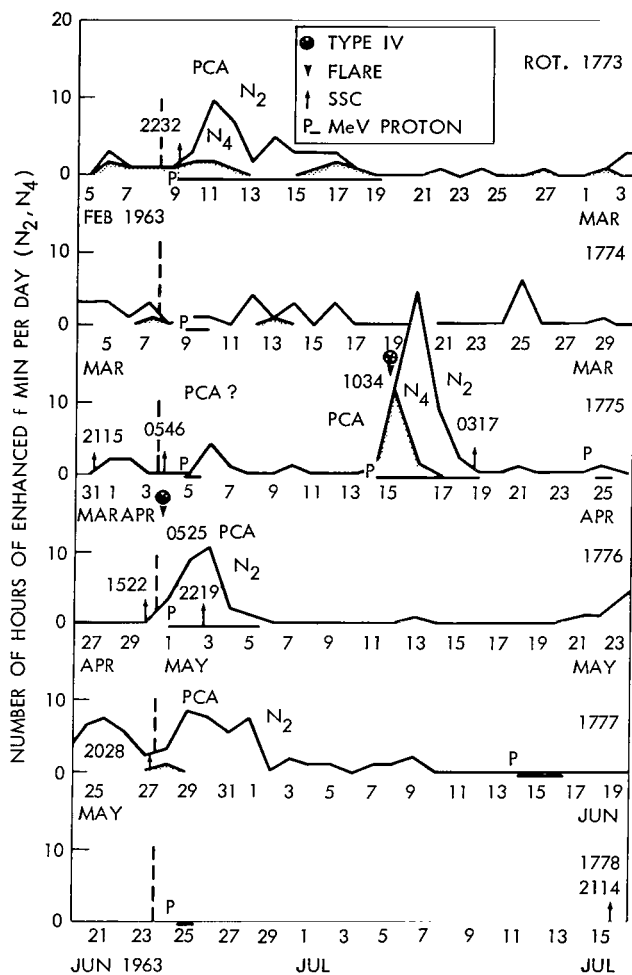


Figure 13—PCA's, Mev proton events, flares, type IV outbursts, and the SSC's observed in solar rotations 1773-78; a recurrent series of PCA's or Mev proton events is indicated by vertical dotted lines.

detector (Krimigis and Van Allen, 1966). These data together with f_{\min} data (which still have an advantage in retrospectivity or availability for a long time) will afford a tool to examine the recurrence tendency in the low sunspot activity. All low-energy proton observations for solar rotations 1767 through 1811 are shown on the 27-day recurrence table in Figure 15. It is seen that the recurrent series starting from days 5-6 is a really clear one lasting for more than 15 solar rotations in 1963-1964. Figure 15 also shows a 27-day recurrence table for the geomagnetic ΣKp index, digitized in six grades shown at the top of the table. In this case, the recurrence lasted for approximately 25 solar rotations from the end of 1962 to the end of 1964.

An average feature of low-energy proton events during 27-days for solar rotation 1767-84 is shown in Figure 16: (a) the occurrence frequency of Mev proton events, and (b) that of the N_2 index of PCA. In comparison, Figure 16 shows average 27-day variations in (c) geomagnetic ΣKp index and (d) neutron intensity at Deep River, occurrence frequencies of (e) type IV outbursts, and (f)

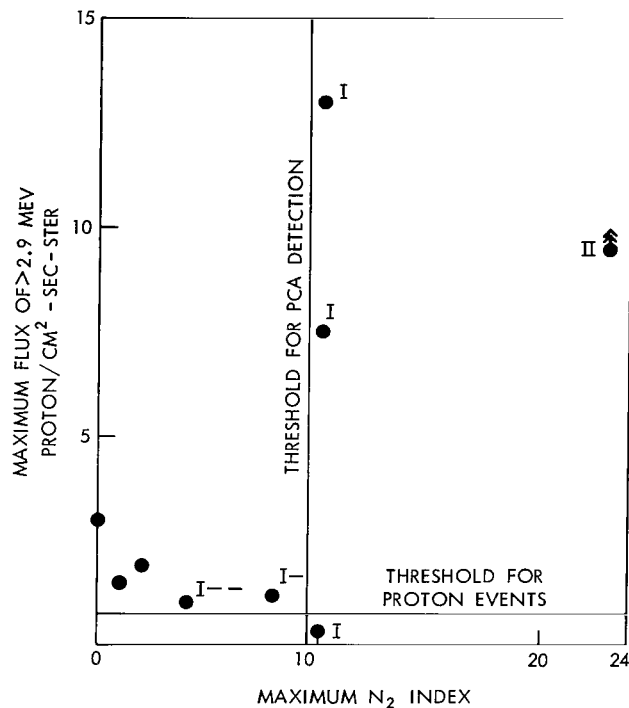








Figure 14—Relationship between maximum flux of Mev proton events and maximum N_2 index of PCA given in Figure 13.

events during the low solar activity period. In recent years, the measurable energy range by space vehicles has continually decreased; numerous increases of solar cosmic-ray intensity have been detected, for example, by the IMP-1 with the 1-Mev proton detector (Fan *et al.*, 1965), and by the Mariner IV with the 0.5-Mev

B: BRYANT ET AL. (1965)
 F: FAN ET AL. (1965)
 K: KRIMIGIS AND VAN ALLEN (1966)
 f: FMIN INDEX, $N_2 \geq 4$.

$\Sigma p =$  0~6  7~13  14~20
 21~27  28~33  34~

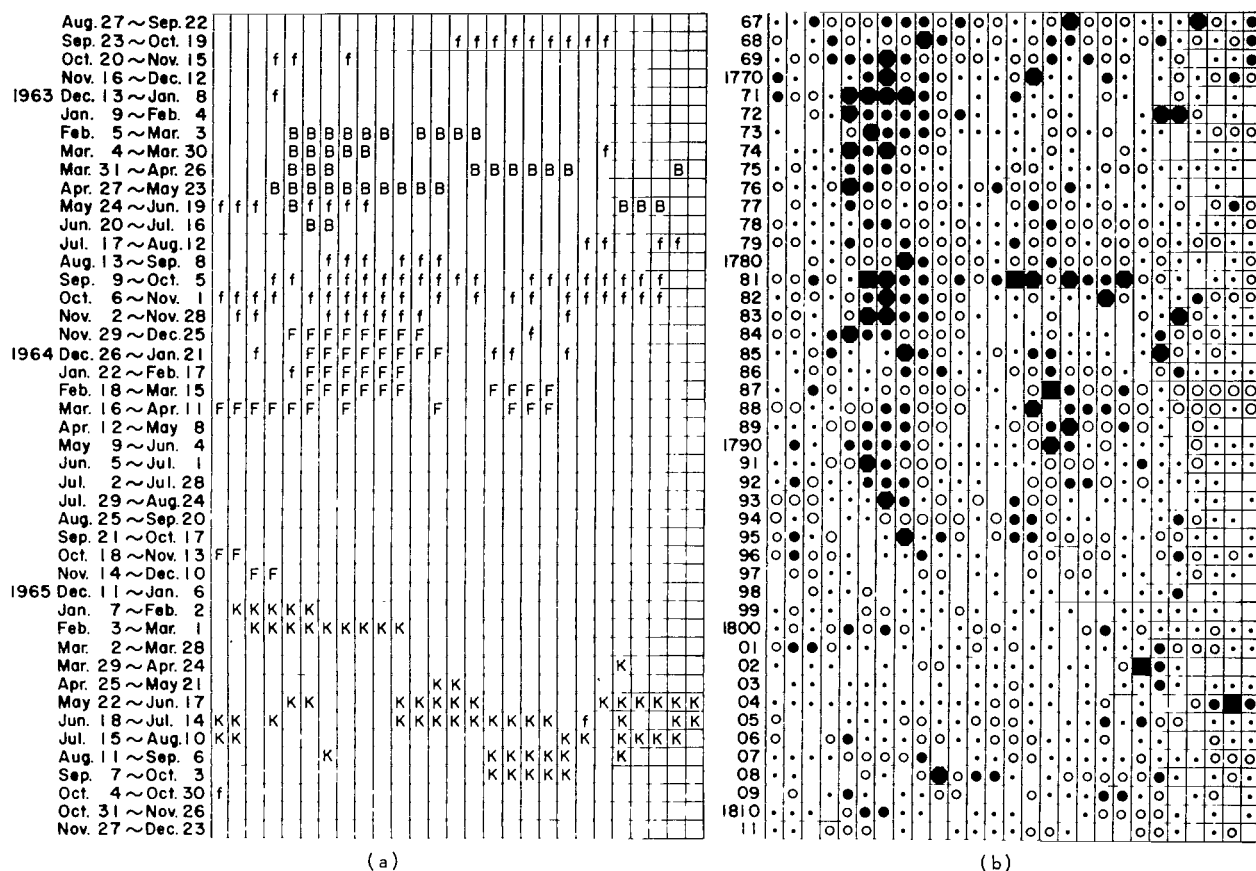


Figure 15—Twenty-seven-day recurrence tables of (a) low-energy solar proton events and (b) geomagnetic ΣKp index, for solar rotations 1767-1811.

CMP dates of the source regions. Predominating peaks observed from the 5th to 12th days in (a) and (b) are caused by the recurrent series of solar Mev proton events. This series coincides with those of (c) geomagnetic ΣKp -index and of (d) neutron intensity variations, which have been reported as traceable for over 20 solar rotations (Mori *et al.*, 1964). Thus, it can be said that the Mev protons were confined within a region corotating with the sun which causes an enhancement of geomagnetic activity and at the same time modulates the galactic cosmic radiations at the orbit of the earth with the 27-day recurrent period.

The distribution of type IV outbursts shown in (e) were almost uniform during the 27 days, showing that these recurrent events have no direct connection with any individual major solar flares. The distribution of CMP dates of type IV sources (f) shows that the recurrent series appeared a few days after the CMP of an inactive region of the 23rd-3rd days, and was entirely out

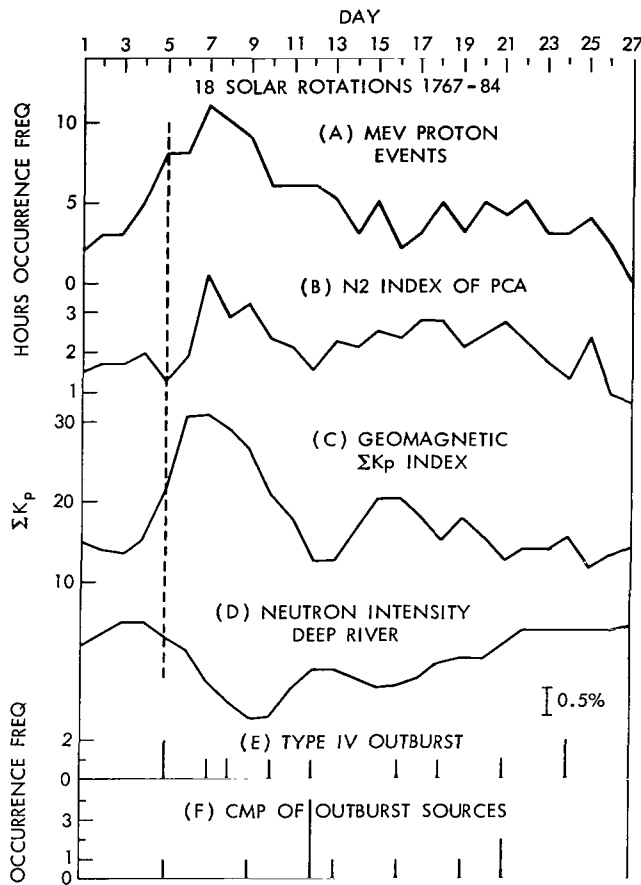


Figure 16—Occurrence frequencies of (a) Mev proton events and (b) N_2 index, average 27-day variations in (c) geomagnetic ΣK_p index and (d) neutron intensity at Deep River (Mori *et al.*, 1964), and occurrence frequencies of (e) type IV outbursts and (f) CMP dates of source regions, for 18 solar rotations 1767–84; August 27, 1962 through December 25, 1963.

with the solar coronal data observed four days earlier, assuming a solar wind velocity of 500 km/s. It is evident that the maxima of ΣK_p and the N_2 index on the 7th day were situated at a sector boundary of the interplanetary magnetic field. This is consistent with a finding by Ness and Wilcox (1965) that the regions of high magnetic field intensity and high solar wind velocity always followed these corotating field reversal regions. As shown elsewhere (Hakura, 1964), the maximum variance of the interplanetary magnetic field observed by Mariner II (Snyder *et al.*, 1963) occurred at the leading part of the velocity enhancement, or at the field reversals.

The turbulence in the interplanetary field may be attributed to Kelvin-Helmholtz instability that developed along the velocity discontinuity (Dessler and Fejer, 1963) and to the sheet pinch instability produced along the field reversal region (Sakurai, 1966). The twisted-fan shaped region of the irregularity corotating with the sun might be the cause of the recurrent cosmic ray modulation shown in Figure 16(d).

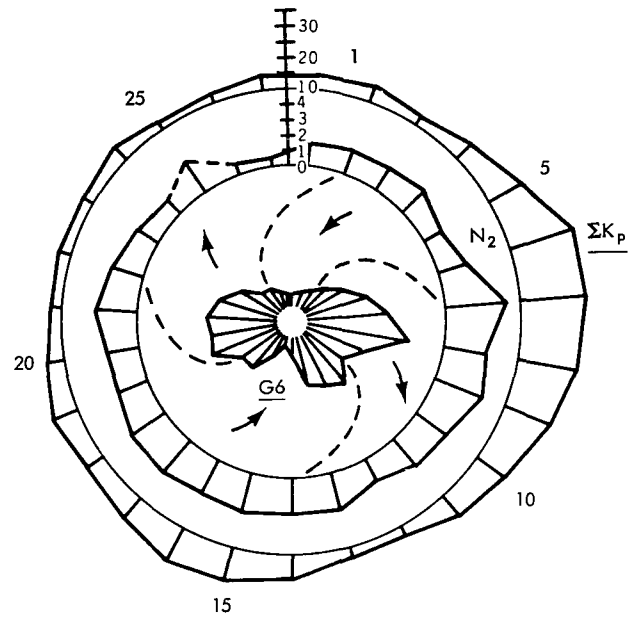


Figure 17—Twenty-seven-day variations in ΣK_p , N_2 index and coronal green line G6, and sector structure of the interplanetary space (Ness *et al.*, 1964).

of phase with the most active region of the 12th day. Figure 17 is another expression of 27-day variations in ΣK_p , N_2 index, and coronal green line G6 (quoted from Sinno, 1964, and Obayashi, 1964), as well as sector structure of interplanetary magnetic field observed by the satellite IMP-1 in the same period (Ness *et al.*, 1964). The dates 5, 10, 15, 20, and 25 are indicated along the ΣK_p variation. The ΣK_p and N_2 observed at the orbit of the earth are connected

The continual presence of Mev proton events, however, needs some particle-acceleration mechanism, and has been explained by the following hypothesis:

- (1) The continuous acceleration of Mev protons exists at the bottom of a sector boundary.
- (2) The continuous acceleration of Mev protons occurs in an active region of the sun, and energetic particles produced are stored in the interplanetary magnetic field for a few solar rotations.
- (3) The continuous acceleration of Mev protons occurs in the interplanetary space in turbulent interface.

The first hypothesis seems to be unreasonable since the Mev protons are connected with an inactive region of the coronal emission as shown in Figure 17. The old active region proposed by Mustel (1961) cannot be the root of the present sector boundary, since days 2-6 remained inactive throughout the last sunspot cycle as shown at the top of Figure 10.

To support the second hypothesis, there was a rather active region that appeared during the third period of PCA activity (III). If this region is connected with the turbulent region with a bottle-shaped interplanetary field, then the solar cosmic rays produced in the active region will propagate along, and be stored in the magnetic bottle, especially in the turbulent magnetic region.

Statistics shown in Figure 18 might support the present hypothesis, where solar cycle variations in \bar{N}_2 and \bar{N}_4 indices (top), ratio \bar{N}_2/\bar{N}_4 (middle), and the 27-day autocorrelation coefficient of ΣKp (bottom) are given. It was noted that variations in \bar{N}_4 and \bar{N}_2 were almost parallel during the high sunspot number, while the ratio \bar{N}_2/\bar{N}_4 became greater in 1961 through 1963. This shows that the Mev proton events represented by enhancement of N_2 index became predominant during the decreasing period of sunspot activity, when the recurrence of geomagnetic activity ΣKp also was enhanced. However, an important point here is the difference between \bar{N}_2 and the autocorrelation coefficient in 1964. The PCA-producing Mev proton was absent, $N_2 = 0$, while a still sound sector structure of interplanetary space existed as shown by a high value of the autocorrelation coefficient

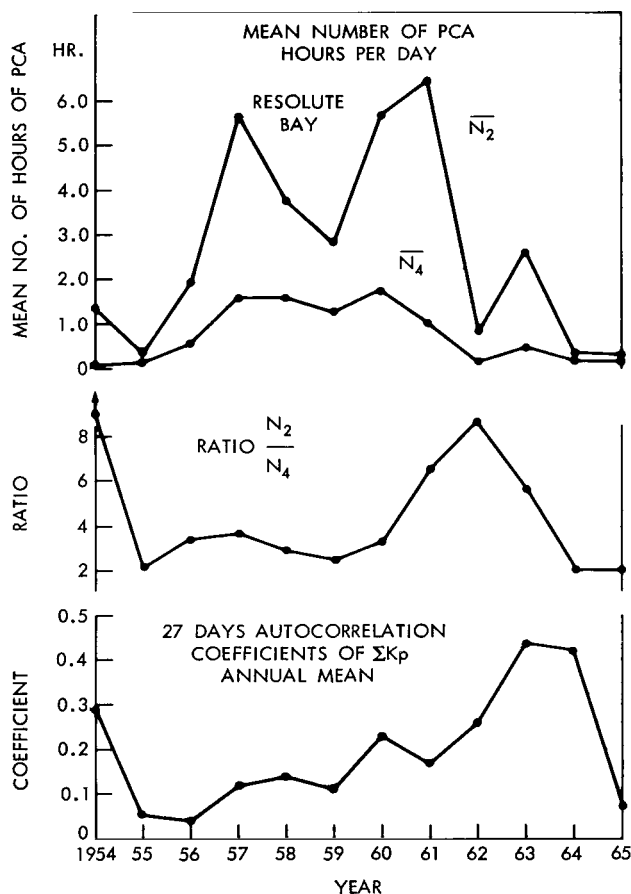


Figure 18—Solar cycle variations in (a) mean N_4 and N_2 indices, (b) ratio N_2/N_4 , and (c) 27-day autocorrelation coefficients of ΣKp .

in 1964. The appearance of recurrent PCA's, i.e. Mev proton events, is caused by the formation of a solid sector structure of the interplanetary space. However, it is also controlled strongly by the type IV activity discussed in Figure 7.

As pointed out by Fan *et al.* (1965), the third hypothesis cannot explain all of the field-reversing corotating regions do not contain Mev protons at all times. However, it is interesting to note that the long-lived recurrent storms of galactic cosmic rays were observed only when the same sector boundary swept the earth. Though we do not have any evidence that supports the peculiarity of the present sector boundary, this hypothesis still survives.

CONCLUSION

Daily indices of PCA activity were computed for years 1954-1965, which covers the whole period of the 19th solar cycle. Outstanding PCA events were selected on the basis of the activity indices and correlated with other solar-terrestrial phenomena such as solar flares, type IV radio outbursts, and geomagnetic storms. A study of the solar-terrestrial relationship was made using the daily indices, the table of outstanding events, and satellite observations of low-energy solar protons. Several important results of the solar cycle variation in the corpuscular activity are summarized as follows:

1. A close correlation between PCA's and type IV solar radio outbursts holds throughout the whole solar cycle considered here, especially for events of major importance. The correlation was increased when propagation conditions for PCA-producing particles in interplanetary space were considered. A statistical study showed an east-west asymmetry of a PCA-producing probability of type IV sources and also a deficiency of PCA-occurrence in northern winter months.

2. Solar corpuscular activity inferred from occurrence frequencies of PCA's and type IV outbursts showed three peaks during the last solar cycle—two outstanding peaks in 1957 (I) and 1960 (II) and a small peak in 1963 (III). During the first peak of activity (I), the type IV sources appeared equally in both the northern and southern hemispheres of the sun. However, the active centers existed only in the northern hemisphere during the later phases of solar activity (II) and (III). Consequently, the heliographic-latitude time distribution of type IV sources showed a complicated pattern with three wings in the northern hemisphere, which is different from the Maunder's simple butterfly diagram obtained for sunspot regions.

3. There was a tendency of the PCA flares to occur in the same active regions even for a few solar rotations. A statistic of the longitudinal distribution of CMP dates of the active centers showed that there were at least four active regions in the period (I), while the active regions were restricted in two parts of narrow heliographic longitudes in the periods (II) and (III). Throughout the whole solar cycle there were two definitely inactive longitude regions on the second through the sixth days and the 17th day of solar rotation. The localization of active centers in the later phase of solar activity might be connected with a simple sector pattern of interplanetary magnetic field revealed by the satellite IMP-1.

4. The solar cycle variations in both the annual mean of geomagnetic ΣKp index and occurrence frequency of the SSC (geomagnetic storms with sudden commencement) showed two peaks in periods (I) and (II). Because of the sporadic nature of the SSC occurrence, the 27-day autocorrelation coefficient of ΣKp was very low for the first period (I). On the other hand, the locality of flare sources enhanced the coefficient in the period (II). The solar cycle variation in the SG occurrence (SG \bar{e} represents a gradual geomagnetic storm) was similar to that in 27-day coefficients; both of them increased toward the end of the solar cycle and had a prominent peak in period (III). The sawtooth distribution of the non-SC recurrent storm occurred with 11- (and possibly 33-) year periodicity in the years 1924 through 1965.

5. During the later phases of solar corpuscular activity (II) and (III), various space vehicles detected a number of solar Mev protons which sometimes caused a slight PCA event detectable by the daily PCA index of higher sensitivity (N_2). A recurrent series of the Mev protons starting from the fifth through the sixth days lasted for approximately 15 solar rotations in 1963-1964. This series coincided with a part of recurrent series of geomagnetic ΣKp index and galactic cosmic-ray variations, which were traceable for approximately 25 solar rotations, ranging from the end of 1962 to the end of 1964. The result means that the Mev protons were confined within a region corotating with the sun; this region caused an enhancement of geomagnetic activity and at the same time modulated the galactic cosmic-ray intensity at the orbit of the earth with a 27-day recurrent period. The maxima of ΣKp and Mev proton activity on the seventh day were situated at a field reversal region of the interplanetary magnetic field observed by IMP-1. The root of the field reversal region was identified with the persistently inactive region of PCA productivity and coronal green line G6 intensity.

6. The appearance of recurrent PCA's or Mev protons is no doubt correlated with the formation of a solid sector structure of the interplanetary magnetic field. However, it is also strongly controlled by the productivity of low-energy solar protons. Our available materials seem to support a hypothesis that the continuous acceleration existed in an active region of the sun, and energetic particles produced were stored in the interplanetary magnetic field for a few solar rotations.

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